CENTRAL VALLEY
FLOOD MANAGEMENT
PLANNING PROGRAM

FloodSAFE
CALIFORNIA

Public Draft

2012 Central Valley Flood Protection Plan

Attachment 8A: Hydrology

January 2012

STATE OF CALIFORNIA
THE NATURAL RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES

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1.0 Introduction

This section states the purpose of this attachment, gives background information (including a description of planning areas, goals, and approaches), discusses assumptions and limitations to the data, and provides an overview of the hydrology report organization.

1.1 Purpose of this Attachment

As part of development of the 2012 Central Valley Flood Protection Plan (CVFPP), a series of technical analyses were conducted to evaluate hydrologic, hydraulic, geotechnical, economic, ecosystem, and related conditions within the Sacramento and San Joaquin river basins flood management system and to support formulation of system improvements.

An important step in conducting these analyses was to establish existing (No Project) hydrologic conditions on a regional/generalized basis. Hydrologic conditions were input into hydrologic and hydraulic models, as described in subsequent attachments.

The 2012 CVFPP used a subset of the hydrology developed for the *Sacramento and San Joaquin River Basins Comprehensive Study* (Comprehensive Study) (USACE and DWR, 2002a). Hydrology from the Comprehensive Study is applicable for use in the 2012 CVFPP because no major flood has occurred in the Sacramento and San Joaquin river basins to modify the hydrology since development of the Comprehensive Study (the last major flood occurred 5 years before the study, in 1997). While levee repairs and improvements have been made since the Comprehensive Study, channel and floodplain conditions in the Sacramento and San Joaquin river basins have not altered significantly.

The 2012 CVFPP hydrology used six of the seven Comprehensive Study synthetic annual exceedence probability (AEP) storm events: 10, 4, 2, 1, 0.5, and 0.2 percent. The 50 percent AEP storm was not used because the Sacramento and San Joaquin river basins' flood management system was assumed to handle storms of at least this magnitude.

To reduce the complexity of analysis for the CVFPP, 10 of the 23 flood runoff centerings (storm centerings) from the Comprehensive Study were used for the 2012 CVFPP hydrology to provide peak flows as input into the riverine hydraulic models (refer to Section 3 for more details). The following five Sacramento River Basin storm centerings were used to develop hydrographs for use as inputs to the reservoir operations and riverine hydraulic models:

- Shasta Lake to Ord Ferry (Shasta-centered)
- Ord Ferry to Feather River (Ord Ferry-centered)
- Yuba River near Marysville (Yuba-centered)
- Sacramento River at the latitude of Sacramento (Sacramento-centered)
- American River at Fair Oaks (American-centered).

Five San Joaquin River Basin storm centerings were used as inputs to the reservoir operations and riverine hydraulic models, as follows:

- San Joaquin River at Friant (Friant-centered)
- San Joaquin River at the latitude of El Nido (El Nido-centered)
- San Joaquin River at the latitude of Newman (Newman-centered)
- San Joaquin River at the latitude of Vernalis (Vernalis-centered)
- Merced River at Exchequer (Exchequer-centered)

Figure 1-1 shows the locations of the 10 storm centerings used for the 2012 CVFPP. These locations were chosen because they are either on the mainstem of the rivers (i.e., produce large runoff on a basin-wide level) or are on major tributaries (i.e., generate extremely large floods on individual rivers).

The following sections summarize Comprehensive Study Appendix B – Synthetic Hydrology, which includes the assumptions, hydrologic analyses, and findings used to develop the Comprehensive Study hydrology (USACE and DWR, 2002b). As stated above, portions of this hydrology were used as inputs for the 2012 CVFPP technical analyses.

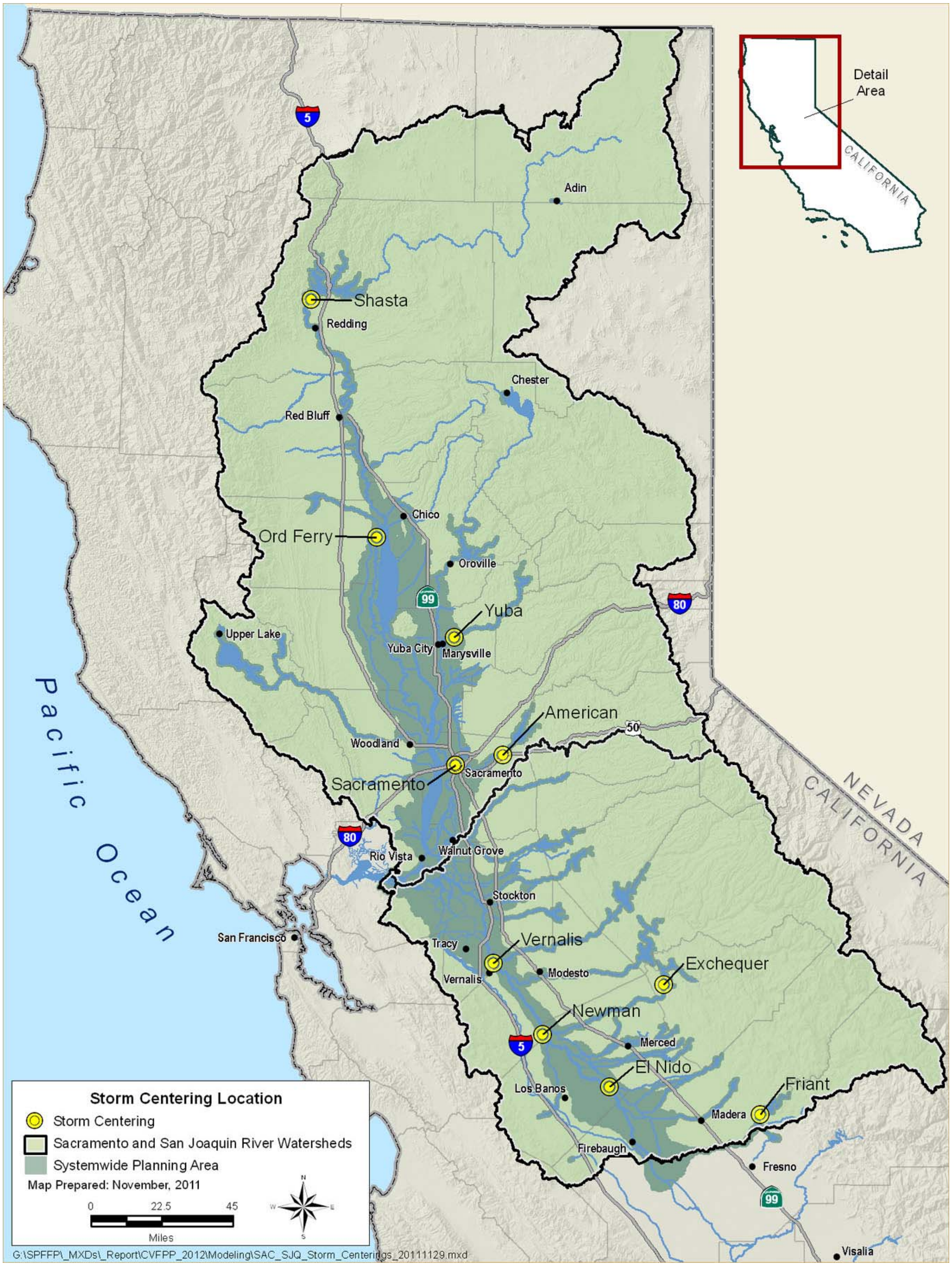

Figure 1-1. 2012 Central Valley Flood Protection Plan Storm Centering Locations

1.2 Background

As authorized by Senate Bill 5, also known as the Central Valley Flood Protection Act of 2008, the California Department of Water Resources (DWR) has prepared a sustainable, integrated flood management plan called the CVFPP, for adoption by the Central Valley Flood Protection Board (Board). The 2012 CVFPP provides a systemwide approach to protecting lands currently protected from flooding by existing facilities of the State Plan of Flood Control (SPFC), and will be updated every 5 years.

As part of development of the CVFPP, a series of technical analyses were conducted to evaluate hydrologic, hydraulic, geotechnical, economic, ecosystem, and related conditions within the flood management system and to support formulation of system improvements. These analyses were conducted in the Sacramento River Basin, San Joaquin River Basin, and Sacramento-San Joaquin Delta (Delta).

1.3 CVFPP Planning Areas

For planning and analysis purposes, and consistent with legislative direction, two geographical planning areas were important for CVFPP development (Figure 1-2):

- **SPFC Planning Area** – This area is defined by the lands currently receiving flood protection from facilities of the SPFC (see *State Plan of Flood Control Descriptive Document* (DWR, 2010)). The State of California's (State) flood management responsibility is limited to this area.

- **Systemwide Planning Area** – This area includes the lands that are subject to flooding under the current facilities and operation of the Sacramento-San Joaquin River Flood Management System (California Water Code Section 9611). The SPFC Planning Area is completely contained within the Systemwide Planning Area which includes the Sacramento River Basin, San Joaquin River Basin, and Delta regions.

Planning and development for the CVFPP occurs differently in these planning areas. The CVFPP focused on SPFC facilities; therefore, evaluations and analyses were conducted at a greater level of detail within the SPFC Planning Area than in the Systemwide Planning Area.

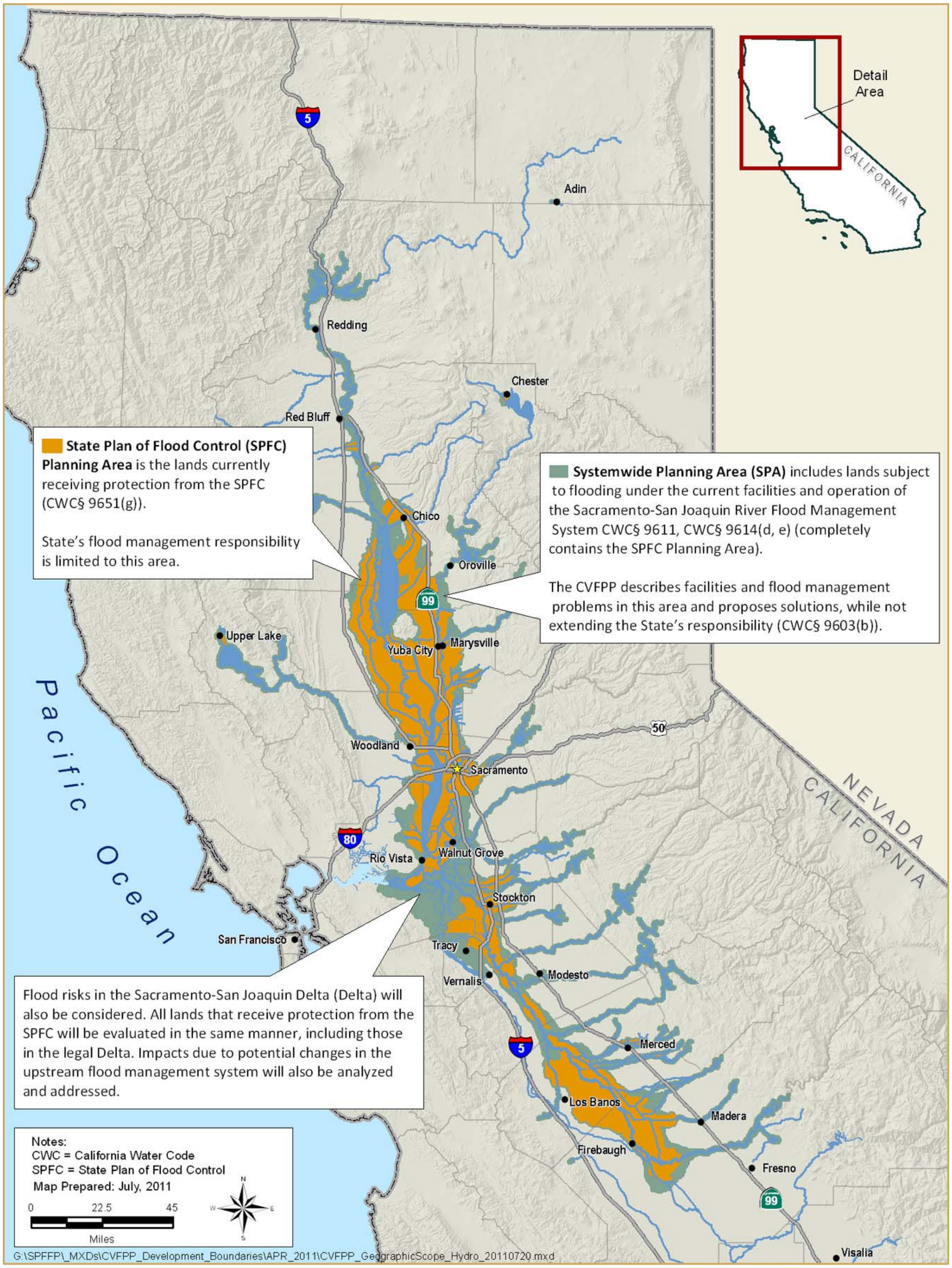

Figure 1-2. Central Valley Flood Protection Plan Planning Areas

Hydrology development for the 2012 CVFPP extends beyond the Systemwide Planning Area and encompasses the Sacramento and San Joaquin river basins.

1.4 2012 CVFPP Planning Goals

To help direct CVFPP development to meet legislative requirements and address identified flood-management-related problems and opportunities, a primary and four supporting goals were developed:

- **Primary Goal** – Improve Flood Risk Management
- **Supporting Goals**:
    - Improve Operations and Maintenance
    - Promote Ecosystem Functions
    - Improve Institutional Support
    - Promote Multi-Benefit Projects

The hydrology discussed in this attachment was used as the basis for the hydrologic and hydraulic modeling performed. Results from the models subsequently enabled assessments of the relative potential of different actions to achieve these goals.

1.5 2012 CVFPP Planning Approaches

In addition to **No Project**, three fundamentally different approaches to flood management were initially compared to explore potential improvements in the Central Valley. These approaches are not alternatives; rather, they bracket a range of potential actions and help explore trade-offs in costs, benefits, and other factors important in decision making. The approaches are as follows:

- **Achieve SPFC Design Flow Capacity** – Address capacity inadequacies and other adverse conditions associated with existing SPFC facilities, without making major changes to the footprint or operation of those facilities.
- **Protect High Risk Communities** – Focus on protecting life safety for populations at highest risk, including urban areas and small communities.

- **Enhance Flood System Capacity –** Seek various opportunities to achieve multiple benefits through enhancing flood system storage and conveyance capacity.

Comparing these approaches helped identify the advantages and disadvantages of different combinations of management actions, and demonstrated opportunities to address the CVFPP goals to different degrees.

Based on this evaluation, a **State Systemwide Investment Approach** was developed that encompasses aspects of each of the approaches to balance achievement of the goals from a systemwide perspective, and includes integrated conservation elements. Figure 1-3 illustrates this plan formulation process.

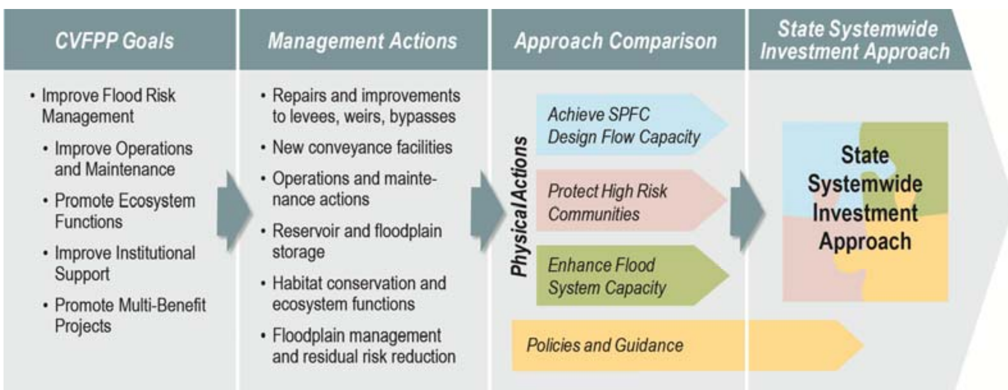

Figure 1-3. Formulation Process for State Systemwide Investment Approach

As described above, this attachment lays the foundations for numerous technical analyses preformed to support the 2012 CVFPP. This attachment does not specifically relate to any of the approaches.

1.6 Basic Assumptions and Limitations

The 2002 Comprehensive Study includes a thorough hydrologic analysis of numerous floodplains and tributaries in the Sacramento and San Joaquin river basins. The 2012 CVFPP includes the same basic assumptions and limitations discussed in the Comprehensive Study.

The Comprehensive Study hydrology may or may not fulfill the technical requirements of site-specific investigations within the Sacramento and San Joaquin river basins. Before using the hydrology for any additional studies, the size and scope of each study, even at the prefeasibility level, will need to be evaluated to determine if the Comprehensive Study hydrology can be directly applied. In most cases, more detailed hydrology will need to be performed. Assumptions and limitations for the data and analyses used in the Comprehensive Study include the following:

- Data are stationary.
- Natural flow frequency curves are strictly rainflood frequency curves. Snowmelt runoff is not directly incorporated into the analysis.
- Centering hydrographs are predicated on flood runoff, not precipitation. The approach was driven entirely by historical flow data; precipitation was not used in any portion of the methodology.
- Storm runoff centerings were formulated based on the "Composite Floodplain" concept (refer to Section 3 for more details).
- The unregulated frequency curves computed for the Comprehensive Study were created by following procedures outlined in Bulletin 17B (USGS, 1982).
- Travel times and attenuation factors (Muskingum coefficients) are fixed for all simulated exceedence frequencies.
- Mainstem unregulated flow frequency curves were designed to quantify the total flows that the basins produced in rain floods, not the average natural flows expected at mainstem locations during any of the synthetic exceedence frequency storm events.
- Patterns for synthetic floods are formulated based on historical storms.

1.7 Report Organization

Organization of this document is as follows:

- Section 1 introduces and describes the purpose of this report, provides background information, and discusses assumptions and limitations used in the study.
- Section 2 briefly describes hydrology in the Sacramento and San Joaquin river basins.
- Section 3 describes the methodology used in the hydrologic analyses.
- Section 4 contains references for the sources cited in this document.
- Section 5 lists acronyms and abbreviations used in this document.

2.0 Hydrology Description

Hydrology used for the 2012 CVFPP encompasses the watersheds of the two major river systems in California's Central Valley, the Sacramento River in the north and the San Joaquin River in the south. The watersheds of these river systems have a combined drainage area of more than 43,000 square miles, an area nearly as large as the state of Florida. The watersheds of the Sacramento and San Joaquin rivers are shown in Figure 2-1.

Because of its climate and geography, flooding is a frequent and natural event in the Sacramento and San Joaquin river basins. Historically, the Sacramento River Basin has been subject to floods that result from winter and spring rainfall as well as rainfall combined with snowmelt. The San Joaquin River Basin has been subject to floods that result from both rainfall that occurs during the late fall and winter months, and unseasonable and rapid melting of the winter snowpack during the spring and early summer months.

Sacramento and San Joaquin river basins hydrologic conditions, such as topography, soils, vegetation, climate, temperature, precipitation, snowpack, and the flood management system, are briefly summarized below from Comprehensive Study Appendix B (USACE and DWR, 2002b).

2.1 Sacramento River Basin

The Sacramento River Basin covers an area of 26,300 square miles (above Rio Vista) and is about 240 miles long and up to 150 miles wide. It is bounded by the Sierra Nevada on the east, the Coast Ranges on the west, the Cascade and Trinity mountains on the north, and the Delta on the south. Major tributaries to the Sacramento River include the Feather and American rivers from the east; Cottonwood, Cache, and Putah creeks from the west; and numerous other smaller creeks flowing into the Sacramento River from both the east and west.

Figure 2-1. Sacramento and San Joaquin River Basin Watershed Map

The following text provides an overview of the hydrologic conditions in the Sacramento River Basin:

- **Topography** varies from flat valley areas and low rolling foothills to steep mountainous terrain (see Table 2-1 for elevation and slope data).

- **Soil cover** is moderately deep. Classifications vary from sands, silts, and clays in the valley areas to porous volcanic areas in the northern end of the basin. In the American and Feather river basins, soils range from alluvial deposits in the valley areas to granitic rock in the upper elevations.

- **Vegetation** in the higher elevations of the Sacramento River Basin is dominated by coniferous forest. The foothills and valley areas are dominated by an oak-brush-grassland environment. Extensive valley areas in the Sacramento River Basin are cultivated for agricultural purposes.

- **Climate** is temperate and varies according to elevation. In the valley and foothill areas, summers are hot and dry and winters are cool and moist.

- Average annual **temperatures** (degrees Fahrenheit (°F)) in the Sacramento River Basin range from the mid-60s in the valley areas to the low 50s at the higher elevations. Temperatures can range from nearly 120°F in the northern valley to below zero in the Sierra Nevada Range.

- Normal annual **precipitation** amounts vary widely throughout the basin, ranging from the low teens in valley areas to 90 inches in some mountain areas. The Sierra Nevada and Coast Ranges have an orographic effect on precipitation. Precipitation increases with altitude, but basins on the east side of the Coast Ranges lie in a rain shadow and receive considerably less precipitation than do basins of similar altitude on the west side of the Sierra Nevada.

- While convective rainfall in the Sierra Nevada can occur in the summer, precipitation is often in the form of **snowpack** at elevations over 5,000 feet above mean sea level (msl) in the Sacramento River Basin during winter and early spring months. Elevations in the northern portion of the Sacramento River Basin reach nearly 14,000 feet above msl in the headwaters of the Sacramento River. Lassen Peak, which exceeds 10,000 feet above msl in the Cascade Range, receives as much as 90 inches of annual precipitation, primarily as snow.

- The basic **flood management system** in the Sacramento River Basin consists of a series of levees and bypasses placed to protect specific areas and take advantage of the natural overflow basins. The flood management system includes levees along the Sacramento River south of Ord Ferry; levees along the lower portion of the Feather, Bear, and Yuba rivers; and levees along the American River. Additionally, the system benefits from three natural drainage basins: Butte, Sutter, and Yolo. These basins run parallel to the Sacramento River and receive excess flows from the Sacramento, Feather, and American rivers via natural overflow channels and over weirs. When the Sacramento River is high, the three basins form one continuous waterway.

Table 2-1. Sacramento River Watershed Topography

Reach	Elevation Range (feet above mean sea level[1])	Slope
Sacramento River Basin above Shasta Dam	1,000 feet to over 14,000 feet	Varies
Sacramento River Basin below Shasta Dam and above Red Bluff	280 feet to approximately 10,000 feet	5 feet per mile
Red Bluff to Ord Ferry	Less than 100 feet to 10,000 feet	1 foot per mile
Ord Ferry to Fremont Weir	Less than 100 feet to 3,000 feet	0.9 feet per mile
Below Fremont Weir	0 feet to 10,000 feet	0.4 feet per mile
Feather and American rivers	Less than 50 feet to 10,000 feet	Varies

Note:
[1] Mean sea level is at 0 feet.

In addition to the leveed system, the flood management system uses reserved flood storage space in selected reservoirs on the Sacramento, Feather, and American rivers and some of their larger tributaries. These reservoirs help to reduce damaging rain flood peaks by holding back floodwaters and, ideally, releasing water into the rivers at a slower rate. Additional information on the flood management system in the Sacramento River basin can be found in the *State Plan of Flood Control Descriptive Document* (DWR, 2010).

2.2 San Joaquin River Basin

The San Joaquin River Basin lies between the crests of the Sierra Nevada and Coast Ranges and extends from the northern boundary of the Tulare Lake Basin, near Fresno, to the Delta, near Stockton, as shown in Figure 2-1. The basin has an area of about 13,500 square miles, as measured at Vernalis, extending about 120 miles from the northern to southern boundaries. Major tributaries to the San Joaquin River include the Fresno, Chowchilla, Merced, Tuolumne, and Stanislaus rivers from the east, and numerous other smaller creeks flowing into the San Joaquin River from both the east and west.

The following text briefly provides an overview of hydrologic conditions in the San Joaquin River Basin:

- **Topography** varies in the San Joaquin River Basin. The Sierra Nevada Range has an average crest elevation of about 10,000 feet above msl with occasional peaks as high as 13,000 feet above msl. Crest elevations of the Coast Ranges reach to about 5,000 feet above msl. The valley area measures about 100 miles by 50 miles and slopes gently from both sides toward a shallow trough somewhat west of the center of the valley. Valley floor elevations range from 250 feet above msl at the south to near sea level at the Delta. The trough forms the channel for the lower San Joaquin River and has an average slope of about 0.8 feet per mile between the Merced River and Paradise Cut in the Delta.

- **Soils** in the valley basin bottoms are poorly drained and fine textured. Some areas are affected by salts and alkali and require reclamation before they are suitable for crops. Bordering and just above the basin are soils of the fans and floodplains. These soils are generally level, very deep, well drained, nonsaline and nonalkaline, and well suited to a wide variety of crops. The soils of the terraces bordering the outer edges of the valleys generally are of poorer quality with dense clay subsoils or hardpans at shallow depths. These soils generally support pasture and rangeland.

- **Vegetation** types include cultivated crops and pasture grasses, and forbs, hardwood forests, chaparral mountain brush, and coniferous forests. The distribution of these vegetation types is primarily a function of elevation, with cultivated crops located almost entirely in valley floor areas, hardwood forests and chaparral brush located at mid-elevations, and coniferous forests at the higher elevations.

- **Climate** is characterized by wet, cool winters; dry, hot summers; and somewhat wide variations in relative humidity. In the valley area, relative humidity is very low in summer and high in winter. At higher elevations, summers are warm and slightly moist and winters are cold and wet, with significant snow accumulations at higher elevations.

- **Temperatures** vary considerably because of seasonal changes and the large range of elevation. Temperatures in the lower elevations are normally above freezing but range from slightly below freezing during the winter to highs of more than 100°F during the summer. At intermediate and high elevations, the temperature may remain below freezing for extended periods during the winter.

- Normal annual **precipitation** in the basin varies from 6 inches on the valley floor near Mendota to about 70 inches at the headwaters of the San Joaquin River. Most of the precipitation occurs during from November through April. Precipitation is negligible during the summer months, particularly on the valley floor. Similar to the Sacramento River Basin, the Sierra Nevada and Coast Ranges have an orographic effect on precipitation in the San Joaquin River Basin. Precipitation increases with altitude, but basins on the east side of the Coast Ranges lie in a rain shadow and receive considerably less precipitation than do basins of similar altitude on the west side of the Sierra Nevada.

- Precipitation is often in the form of **snowpack** at elevations over 5,000 feet above msl in the San Joaquin River Basin during winter and early spring months. Ground surface elevations in southern portions of the San Joaquin River Basin reach nearly 14,000 feet above msl in the headwaters of the San Joaquin River. These higher elevations relative to the northern Sierra Nevada mean that peak snowmelt lasts longer into the growing season in the San Joaquin River Basin.

- The **flood management system** includes leveed sections along the San Joaquin River; levees along the lower portions of Ash and Berenda sloughs; Bear Creek; and the Fresno, Stanislaus, and Calaveras rivers. The Chowchilla Canal Bypass diverts excess San Joaquin River flow and sends it to the Eastside Bypass. In addition to Chowchilla Canal Bypass flow, the Eastside Bypass intercepts flows from minor tributaries and rejoins the San Joaquin River between Fremont Ford and Bear Creek. Channel capacity on the San Joaquin River decreases moving downstream until its confluence with the Merced River, where San Joaquin River channel capacity then begins to increase. The San Joaquin River levee and diversion systems are not designed to contain the objective release (maximum allowable flow downstream from a reservoir before the beginning of flooding) from each of the project reservoirs simultaneously. Flows in the San Joaquin River that are less than design flow for a given reach may still cause damage to levees in that reach.

In addition to the leveed system, the flood management system uses reserved flood storage space in selected reservoirs on the San Joaquin, Fresno, Chowchilla, Merced, Tuolumne, and Stanislaus rivers and some of their larger tributaries. These reservoirs help to reduce damaging rain flood peaks or snowmelt by holding back floodwaters and, ideally, releasing water into the rivers at a slower rate. Additional information on the flood management system in the San Joaquin River Basin can be found in the *State Plan of Flood Control Descriptive Document* (DWR, 2010).

The San Joaquin River Basin also receives floodflows from the Tulare Lake Basin. The Kings River weirs divert floodflows north via the Kings River North, James Bypass, Fresno Slough, and Mendota Pool system into the San Joaquin River Basin. Flows greater than as specified in flood management operating policies are sent into the Tulare Lake Basin via Kings River South.

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3.0 Hydrologic Analyses

This section summarizes the methodology used during the Comprehensive Study to prepare flood runoff centerings and flood hydrographs that feed into reservoir system (hydrologic) and hydraulic models; those simulations culminated in delineation of floodplains and estimates of potential flooding damages.

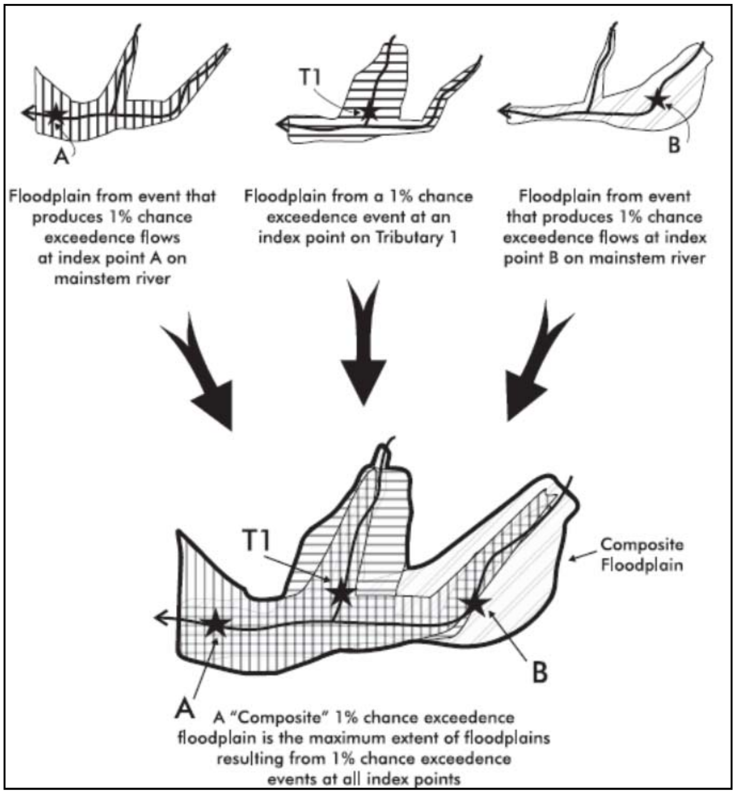
As described in Section 1, a subset of the methods and findings from the Comprehensive Study were used for the 2012 CVFPP. For additional details regarding the Comprehensive Study hydrologic analysis, refer to Comprehensive Study Appendix B (USACE and DWR, 2002b).

Synthetic 50, 10, 4, 2, 1, 0.5, and 0.2 percent AEP storms were developed for the Comprehensive Study. The seven synthetic AEP storms provided a basis for defining existing conditions, analyzing alternatives, and plan formulation. The Comprehensive Study hydrologic analysis, completed by the Water Management Section of the U.S. Army Corps of Engineers (USACE), included following:

- Updated natural flow frequency curves were prepared for locations within the basins
- Retrospective of historical floods that have impacted Central Valley rivers and synthetic flood runoff centerings were developed to represent flood events of a specific exceedence frequency
- Seven synthetic exceedence frequency flood hydrographs were developed

3.1 Composite Floodplain

The Comprehensive Study hydrologic analysis used the "Composite Floodplain" concept, which recognizes that the floodplains generated through modeling of the seven synthetic exceedence frequency events were not created by a single flood event, but by a combination of several events, each of which shaped the floodplain at different locations. This concept is illustrated in Figure 3-1 and further described in *Hydraulic Technical Documentation of the Comprehensive Study* (Comprehensive Study Appendix D) (USACE and DWR, 2002c). Moving downstream in a watershed, a Composite Floodplain becomes increasingly complex. With the confluence of each additional tributary, the number of possible scenarios of flow combinations that could shape the floodplain grows. The role of tributaries in shaping floodplains individually and as a system is the foundation of the Composite Floodplain concept and a cornerstone of the Comprehensive Study's hydrologic analysis. The synthetic hydrology was developed so that the Composite Floodplain represents the maximum extent of inundation possible at all locations for any simulated synthetic exceedence frequency storm events.



Source: USACE and DWR 2002b

Figure 3-1. Composite Floodplain Concept

3.2 Study Approach

The Comprehensive Study's hydrologic analysis investigated three fundamental subjects during the formulation of synthetic flood events:

1. Amount of runoff produced during each of the seven synthetic AEP storms.

2. Contribution of individual tributaries to this total volume.

3. Translation of these flood volumes and distributions to hourly time series for input into a reservoir simulations model.

3.3 Analysis

Unregulated frequency curves were developed at key mainstem and tributary locations in both the Sacramento and San Joaquin river basins in the Comprehensive Study. Unregulated frequency curves plotted historical points and statistical distributions of unimpaired flows (no reservoir influence). Curves displayed volumes or average flow rates for different time durations over a range of AEPs. These curves were used to translate (1) hydrographs to frequencies (e.g., in 1997, the 3-day natural inflow to Friant Dam was roughly 50,000 cubic feet per second (cfs), which translates to a 1.54 percent AEP storm), and (2) frequencies to flood volumes (e.g., according to the curves, the 3-day natural inflow to Friant Dam associated with an annual 10 percent AEP storm is approximately 20,000 cfs). After a curve was developed, runoff volume for any of the seven synthetic exceedence frequency flood events could be obtained from the plot for that curve's specific location.

3.3.1 Methodology for Deriving Unregulated Frequency Curves

The unregulated frequency curves computed for the Comprehensive Study were created by following the procedures outlined in Bulletin 17B, *Guidelines for Determining Flood Flow Frequency* (USGS, 1982). This report directs federal agencies to use the procedures included therein for all "planning activities involving water and related land resources." Bulletin 17B requires the use of a Pearson Type III distribution with log transformation of the data (Log Pearson Type III distribution) as the method to analyze flood flow frequency.

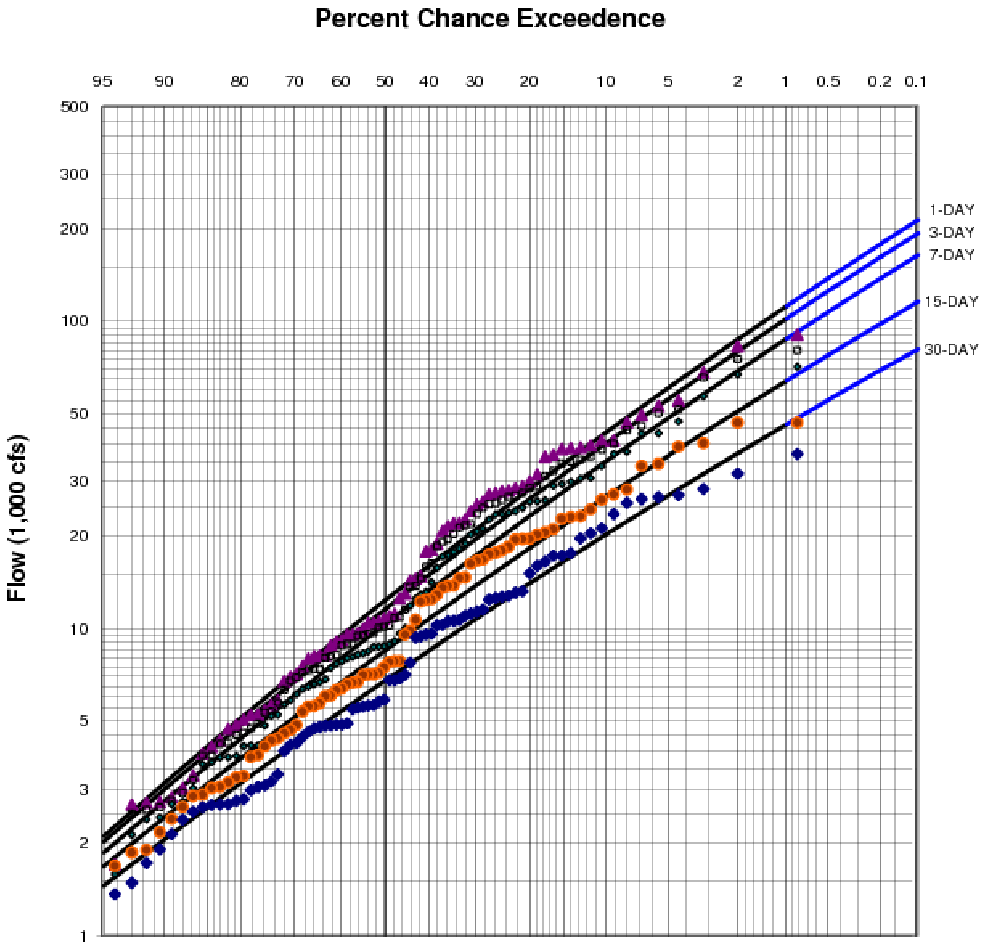
Development of the unregulated frequency curves for the tributaries required daily natural flow data for all target locations. (This development of data is shown in Attachment B.1 to Comprehensive Study Appendix B.) Most of the data were obtained from USACE archives, U.S. Geological Survey (USGS) publications, Central Valley, federal, and other water agencies (including the U.S. Department of the Interior, Bureau of Reclamation, Oroville-Wyandotte Irrigation District, South Sutter Water District, Placer County Water Association, Nevada Irrigation District, Surface Water Data Inc., Southern California Edison, Sacramento Metropolitan Utility District, and Pacific Gas and Electric Company). Data from tributaries were routed to downstream locations for use in constructing mainstem "index" frequency curves.

Unregulated frequency curves for the Sacramento and San Joaquin river basins used for the Comprehensive Study are documented in Attachment B.2 to Comprehensive Study Appendix B. These curves were derived from a statistical analysis of the recorded data after the data had been transformed to log values. The mean, standard deviation, and skew of the log-transformed data were computed for each stream gage or reservoir. The data were screened for high and low outliers and, if found, adjustments to the statistics were computed as outlined in Bulletin 17B. In addition, the resulting statistics were reviewed and sometimes adjusted or smoothed to account for sampling error differences among the various durations, or after comparison with similar gages in a watershed or region. Each frequency curve also plots historical flood events, given their estimated frequency. Determination of a historical event using a frequency plot is described in Comprehensive Study Appendix B (USACE and DWR, 2002b).

Unregulated frequency curves were prepared for 8 mainstem locations and 43 tributary locations (i.e., 51 curve sets), as shown in Attachment B.2 to Comprehensive Study Appendix B. An example of an unregulated frequency curve is shown in Figure 3-2. In all cases, curves were developed or updated to reflect post-1997 hydrology. For any location, the amount of runoff volume produced during simulation of any of the seven synthetic exceedence frequency flood events can be read from the family of best-fit curves or computed directly from the final statistical distribution of each duration. For example, the 1 percent AEP (100-year) 30-day runoff volume for the San Joaquin River near Newman, shown in Figure 3-2, can be determined by reading the average flow of 46,000 cfs, multiplying by the number of seconds in 30 days, and dividing by 43,560 to get 2.7 million acre-feet.

The approach formulated for the hydrologic analysis was driven entirely by historical flow data. Each year of record included the influence of snowmelt, infiltration, interception, precipitation distribution, timing of runoff, storm development characteristics, and physical basin attributes for that annual rain flood event. Historical flow data records provided a sufficient sample of flood events to characterize hypothetical flood volumes and tributary system relationships.

No synthetic precipitation events were required in development of the Comprehensive Study hydrology; precipitation was not used in any portion of the methodology.



ADOPTED STATISTICS:

	Mean	Std.Dev.	Skew
1-day	4.079	0.445	-0.2
3-day	4.052	0.439	-0.2
7-day	4.002	0.431	-0.2
15-day	3.918	0.407	-0.2
30-day	3.820	0.387	-0.2

NOTES:

1. No overbank flow.
2. Median plotting positions.
3. Drainage area: 9,520 sq. mi.
4. Period of record: 1917-1998.

SACRAMENTO-SAN JOAQUIN COMPREHENSIVE STUDY
SAN JOAQUIN RIVER BASIN, CALIFORNIA

RAIN FLOOD FREQUENCY CURVES
SAN JOAQUIN RIVER NEAR NEWMAN
UNREGULATED CONDITIONS

U.S ARMY CORPS OF ENGINEERS
SACRAMENTO DISTRICT

Source: USACE and DWR 2002b

Figure 3-2. Example Rain Flood Frequency Curves – San Joaquin River near Newman

3.3.2 Historical Flood Event Analysis

The historical flood event analyses described in Comprehensive Study Appendix B were based on natural flow data analysis, which resulted in the compilation of the 51 curve sets (8 mainstem and 43 tributary) that quantified flood volumes at discrete locations within the Sacramento and San Joaquin river basins. At mainstem locations, total volumes reflected the combined flows of upstream tributaries. To perform simulations with reservoir and hydraulic models, this total volume needed to be redistributed into the system of tributaries through a flood pattern.

In nature, storms trigger high flows on large-scale river systems and isolated tributaries as a function of storm structure, air temperature, water content, storm path, orographic influence, basin alignment, and many other geophysical and meteorological variables. Ultimately, all storms are unique, but certain dynamics are common to a variety of storm types, especially those that trigger productive (in terms of volume) events in the Sacramento and San Joaquin river basins. Development of patterns is possible through a number of methods, including random generation, use of a singular historical event, and uniform or ramped concurrencies. The most realistic patterns for synthetic floods are formulated based on historical storms. A detailed analysis of several events was undertaken to identify flood trends and distributions that could be incorporated into generalized patterns.

3.3.3 Retrospective of Historical Flood Events

Nineteen historic flood events were analyzed for the Comprehensive Study. These events were chosen based on the natural 3-day rain flood volumes produced at Sacramento and San Joaquin river basins flood management reservoirs. On a project-by-project basis, any event that was both the largest 3-day natural flow experienced during that water year and one of the five largest 3-day natural flows in the gage history of that project was selected for analysis. Although this selection process focused on tributary events, often the same year was selected for multiple projects. This was especially true for the largest flood years on record (i.e., 1956, 1986, and 1997). Therefore, the 19 storms represented a mixed population of storms that focused on individual tributaries as well as storms that had a powerful systemwide effect.

For each year, a time window was set that contained both the tributary event, which had been selected for inclusion that year, and that provided additional time to allow the storm pattern to complete its influence throughout the basin. Duration flows (1-, 3-, 7-, 15-, and 30-day average flows) within this event window were analyzed for all several mainstem locations and significant tributaries. These flows were translated into annual percent chance exceedence values based on the unregulated flow and index frequency curves developed for mainstem and tributary locations during the natural flow analysis.

By comparing AEPs instead of flow rates, the distribution of storm patterns is normalized spatially. Percent chance exceedences provide a consistent measure of intensity from basin to basin, while flow rates, as a function of drainage area, alignment, and other factors, are tributary-specific. Investigating chance exceedences clarifies patterns regarding how individual storm systems impact a system of tributaries. Considering multiple storm events highlights trends linking tributary responses and orographic influence in rare events that form the basis for, and can be incorporated into, the development of generalized storm patterns.

3.3.4 Flood Matrix

All AEP storms, locations of interest, flood durations, and year of event were tabulated into Sacramento River Basin and San Joaquin River Basin storm matrices, referred to jointly as the "Matrix," as shown in Comprehensive Study Appendix B, Attachment B. 3. The Matrix, a valuable product of the Comprehensive Study, includes the 19 historical flood events analyzed for comparison of runoff for all major tributaries in a complex hydrologic system. The matrices are presented upstream to downstream, allowing storm and tributary dynamics to be reviewed in diverse permutations of flood durations, storm combinations, and tributary sets.

The Comprehensive Study matrix investigations pointed to several trends that were eventually incorporated into the synthetic flood runoff centering, such as the presence of spatial trends and storm "bull's eyes" within individual storm events. Bull's eyes were created as historical storms impacted certain spatial areas with greater intensity than surrounding areas. Nearly all events in the Matrix displayed some sort of spatial trend or bias toward a specific area.

Mainstem locations below these bull's eyes experienced greater exceedence frequencies because at those locations the intensity of flooding was a function of all upstream tributaries, not just those that were especially intense. In this sense, the mainstem acted as a buffer that absorbed and moderated localized extremes.

A key finding was that orographic effects were most pronounced in the rarest, least frequently occurring events. Orographic effects in the Sacramento River Basin were definitely visible, but not as well defined as those in the San Joaquin River Basin. It is likely that the more pronounced orographic influence in the southern Central Valley is related to the average ridge crest elevation along the Sierra Nevada, which is generally lower in the Sacramento River Basin than in the San Joaquin River and Tulare Lake basins; however, this remains uncertain.

The Matrix also showed that natural dynamics are highly variable. Storm cells nested within a larger storm structure are powerful and can trigger individual tributary flooding. Even with supporting evidence for orographic influence, there are Matrix examples of floods that demonstrate a consistently opposite bias; in the San Joaquin River Basin during the March 1995 floods and in the Sacramento River Basin during the 1983 floods, annual percent chance exceedences for foothill tributaries were lower than for neighboring higher basins.

3.4 Synthetic Flood Runoff Centering

The Comprehensive Study's guidelines for flood runoff centering were formulated using the trends identified in the historical storm analysis and the Composite Floodplain concept. A flood runoff centering is defined simply as a set of synthetic exceedence frequencies assigned to a mainstem and/or set of tributaries. As described in Comprehensive Study, Appendix B, centerings were developed separately for the Sacramento and San Joaquin river basins; each tributary was included in all centerings within its basin.

Two basic types of flood runoff centerings were analyzed. The first type consists of basin-wide flood events (mainstem centerings), which are significant on a regional basis and produce large runoff volumes throughout the system. The second type is tributary-specific floods (tributary centerings), which generate extremely large floods in individual rivers, but are not widespread enough to produce the runoff volumes typical of basin-wide events.

3.4.1 Mainstem Flood Runoff Centering

Mainstem centerings were designed to stress widespread areas. Index frequency curves were prepared for the mainstem centerings. These curves provide the hypothetical volumes that a basin will produce during simulations of each of the seven synthetic exceedence frequency flood events. The role of the mainstem centerings was to distribute these volumes back into a basin, tributary by tributary, in accordance with patterns visible in historical flood events. Once the volume was distributed, it was translated into hydrographs and routed through reservoir simulation models to produce the seven synthetic exceedence frequency regulated hydrographs needed to construct floodplains throughout the Sacramento and San Joaquin river basins. Table 3-1 gives an example of a mainstem flood runoff centering and shows the coincident AEP for flows at various locations.

Table 3-1. Example Mainstem Flood Runoff Centering – Sacramento River at Latitude of Ord Ferry

Storm Centering	Flood Event (percent AEP)						
	50%	10%	4%	2%	1%	0.50%	0.20%
Sacramento River at Shasta	81.97	16.92	5.71	2.41	1.25	0.65	0.28
Clear Creek at Whiskeytown	61.73	15.04	9.03	5.61	2.92	1.52	0.65
Cow Creek near Millville	61.73	13.53	8.02	3.89	2.02	1.05	0.45
Cottonwood Creek near Cottonwood	61.73	15.04	9.03	5.61	2.92	1.52	0.65
Battle Creek Below Coleman Fish Hatchery	61.73	13.53	8.02	3.89	2.02	1.05	0.45
Mill Creek near Los Molinos	87.72	**15.04**	7.22	5.94	3.10	1.61	0.69
Elder Creek near Paskenta	87.72	19.34	12.50	10.10	5.26	2.74	1.17
Thomes Creek at Paskenta	87.72	19.34	12.50	10.10	5.26	2.74	1.17
Deer Creek near Vina	87.72	15.04	7.22	5.94	3.10	1.61	0.69
Big Chico Creek near Chico	87.72	15.04	7.22	5.94	3.10	1.61	0.69
Stony Creek at Black Butte	87.72	19.34	12.50	10.10	5.26	2.74	1.17
Butte Creek near Chico	87.72	15.04	10.20	8.42	4.39	2.28	0.97
Feather River at Oroville	87.72	19.34	9.62	8.42	4.39	2.28	0.97
Yuba River at New Bullards Bar	87.72	19.34	11.76	9.18	4.78	2.49	1.06
Yuba River at Englebright	87.72	19.34	11.76	9.18	4.78	2.49	1.06
Deer Creek near Smartsville	87.72	19.34	11.76	9.18	4.78	2.49	1.06
Bear River near Wheatland	87.72	19.34	12.03	10.10	5.26	2.74	1.17
Cache Creek at Clear Lake	87.72	19.34	18.05	12.63	6.58	3.42	1.46
North Fork Cache Creek at Indian Valley	87.72	19.34	18.05	12.63	6.58	3.42	1.46
American River at Folsom	87.72	19.34	14.29	12.63	6.58	3.42	1.46
Putah Creek at Berryessa	87.72	19.34	18.05	12.63	6.58	3.42	1.46

Source: USACE and DWR 2002b
Note:
The values listed for each index point and flood event represent the percent chance of occurrence in any year. For example, during a 10 percent AEP storm centered at Ord Ferry, concurrent flows would be experienced on Mill Creek that correspond to about a 15 percent AEP storm at Mill Creek near Los Molinos (bold).
Key:
AEP = annual exceedence probability

Mainstem centerings reflect a generalized flood pattern based on a number of historical events. Through incorporation of multiple floods into one characteristic pattern, relationships between tributaries become more stable and the influence of powerful, but isolated, storm cells is downplayed.

Characteristic patterns were developed for each mainstem location. When available, historical events that showed flood bull's-eyes in the watershed above the mainstem location of interest were used to formulate synthetic patterns. The orographic effects noted in the Matrix analysis were also incorporated, especially for the largest, less frequently occurring synthetic exceedence frequency events.

To develop patterns consistently, guidelines for mainstem pattern construction were formulated and are presented in Table 7 of Comprehensive Study Appendix B. After an initial pattern was formulated in the Comprehensive Study, hydrographs were constructed at tributary locations (in accordance with the pattern) and routed back to the mainstem location with the same procedure used during construction of the index frequencies, as shown in Attachment B.4 of the Comprehensive Study. Duration maxima (1-, 3-, 7-, 15-, and 30-day) were computed for the mainstem hydrograph and compared with average flows from the index curve. The initial pattern was then increased or decreased by a fixed percentage and the comparison process was repeated. This iterative procedure continued until the final centering produced flood volumes at the mainstem location that were roughly equal to the hypothetical volumes specified by the index curves.

3.4.2 Tributary Flood Runoff Centering

Tributary centerings were designed to stress individual tributary systems. Whereas the mainstem centerings were formulated as spatially distributed events that were productive on a systemwide basis, tributary centerings were designed to simulate extreme floods on individual rivers generated by storm systems that were not widespread enough to produce runoff volumes typical of basin-wide events. In this sense, tributary centerings seek to reflect the powerful and isolated storm cells intentionally downplayed by the mainstem centerings. Development of tributary centering is further described in Comprehensive Study Appendix B (USACE and DWR, 2002b).

Once a tributary centering was prepared, it was deemed complete pending a test that translated centerings to hydrographs and routed tributary flows to the nearest downstream index curve location. Duration maxima (1-, 3-, 7-, 15-, and 30-day) were then computed for each of the resultant seven synthetic exceedence frequency natural flow hydrographs and compared with average flows from the corresponding index frequency curves. For each tributary centering, it was confirmed that the flows experienced at the mainstem points were lower than those generated by the corresponding mainstem centering. This affirmed that the floodplains in mainstem locations were more likely to be shaped by the widespread floods simulated with mainstem centerings.

3.4.3 Development of Seven Synthetic AEP Storm Natural Flow Hydrographs

Storm frequencies, described above, needed to be translated to hourly flood flow hydrographs for use in reservoir simulations and hydraulic modeling. The Comprehensive Study's translation process involved three steps:

1. Obtaining average floodflow rates from unregulated tributary frequency curves.

2. Separating these average flows into wave volumes.

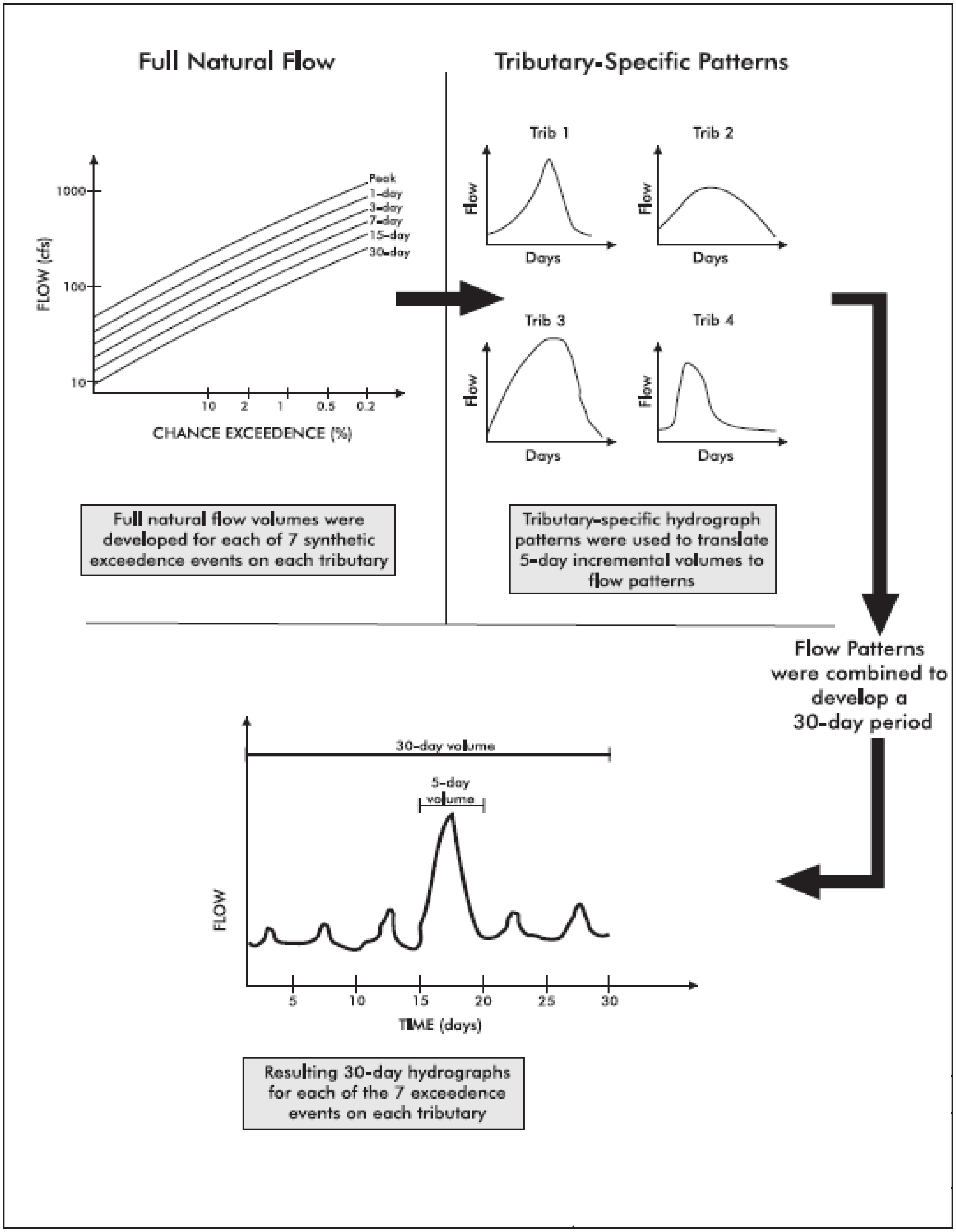
3. Combining and distributing volumes into a six-wave series of 5-day waves covering a 30-day flood period.

This process was performed only at tributary locations; mainstem flood hydrographs always resulted from the routed contributions of upstream tributaries. The process is illustrated in Figure 3-3 and Plate 4 in Comprehensive Study Appendix B (USACE and DWR, 2002b).

Values from the unregulated frequency curves represented the average flow anticipated over a specific time interval. For instance, the 5-day value was the average flow expected during the highest 5 days of flooding during any of the seven synthetic exceedence events. Likewise, the 10-day value was the average over the highest 10 days of flooding, etc. Although not always the case, it was typical for the highest 5-day period to be part of the highest 10-day period as well as part of the highest 15-day, 20-day, and other periods.

Flood volumes were computed by multiplying average flows by their respective durations. These values represented the total volumes of water anticipated during the highest 5, 10, 15, 20, 25, or 30 days of flows. The volumes were portioned into time segments by subtracting volumes of the shorter durations from the next longer duration (i.e., 5-day volume is subtracted from 10-day volume to calculate the volume produced between the extents of the 5-day and 10-day periods. This procedure was repeated for the 10-, 15-, 20-, 25-, and 30-day durations and resulted in a set of seven synthetic exceedence frequency flood volumes produced by a tributary. These seven volumes were treated as wave volumes in a series of six 5-day waves.

In the Comprehensive Study, the basic pattern of all synthetic flood hydrographs was a 30-day hourly time series consisting of six waves, each 5 days in duration. Volumes were ranked and distributed into a basic pattern. The highest wave volume was always distributed into the fourth, or main, wave. The second and third highest volumes preceded and followed

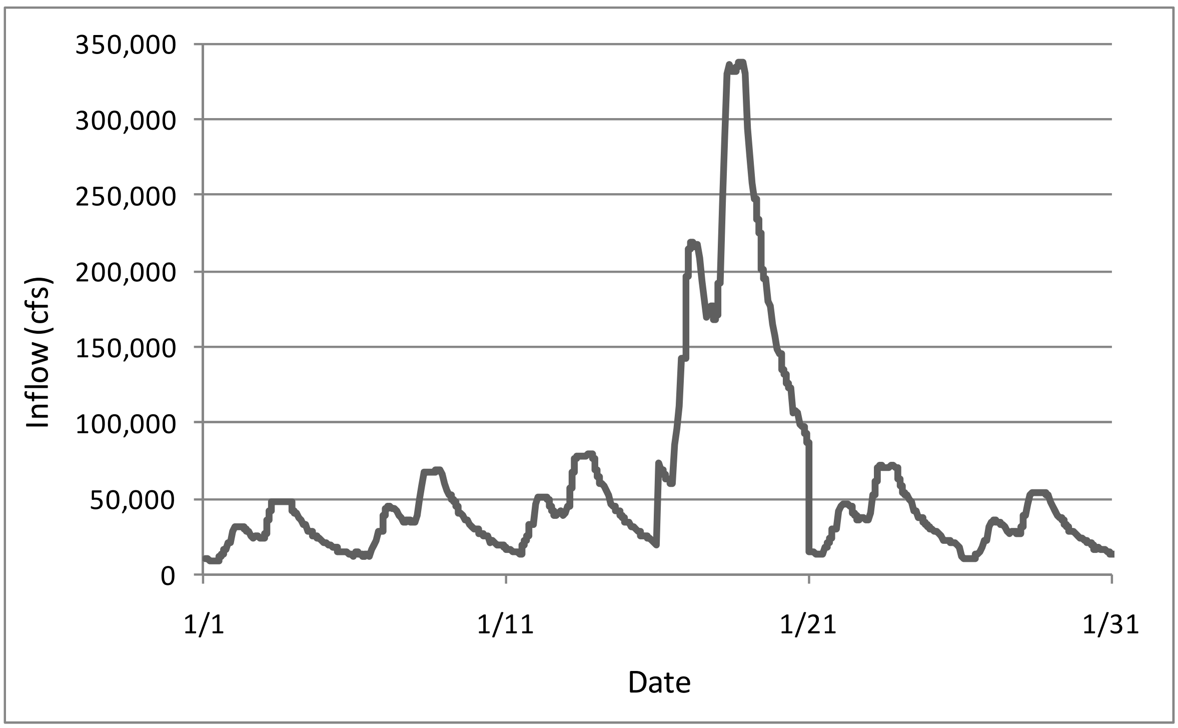


Source: USACE and DWR 2002b

Figure 3-3. Example Synthetic Flood Hydrograph Construction

the main wave, respectively. The fourth highest volume was distributed into the second wave and the fifth highest was distributed into the final of the six waves. The sixth and smallest wave volume was distributed into the first wave of the series. The shape of each wave was identical and the magnitude was determined by the total volume that the wave needed to convey. Figure 3-4 is an example of a synthetic flood hydrograph for inflow into Oroville.

The distribution of tributary flood volumes into 5-day wave patterns was automated using the same spreadsheet that translated frequencies to average flows. Hydrographs were automatically computed and copied into text files for direct entry into the USACE Hydrologic Engineering Center's data storage system used to hold input data for the reservoir operations and hydraulic models.



Source: USACE and DWR 2002b

Figure 3-4. Example Synthetic Flood Hydrograph – 1 Percent AEP Inflow to Oroville

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4.0 References

California Department of Water Resources (DWR). 2010. State Plan of Flood Control Descriptive Document. November.

DWR. *See* California Department of Water Resources.

USACE and DWR. *See* U.S. Army Corps of Engineers and California Department of Water Resources.

U.S. Army Corps of Engineers and California Department of Water Resources (USACE and DWR). 2002a. Sacramento and San Joaquin Rivers Comprehensive Study.

———. 2002b. Appendix B – Synthetic Hydrology Technical Documentation of Sacramento and San Joaquin Rivers Comprehensive Study. Technical Studies Documentation.

———. 2002c. Appendix D – Hydraulic Technical Documentation of the Comprehensive Study.

U.S. Geological Survey (USGS). 1982. Bulletin 17B, Guidelines for Determining Flood Flow Frequency.

USGS. *See* U.S. Geological Survey.

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5.0 Acronyms and Abbreviations

°F.............................. degrees Fahrenheit

AEP .... annual exceedence probability

Board......................... Central Valley Flood Protection Board

cfs............................. cubic feet per second

Comprehensive Study 2002 Sacramento and San Joaquin River Basins Comprehensive Study

Comprehensive Study Appendix B Appendix B, Synthetic Hydrology Technical Documentation, the 2002 Sacramento and San Joaquin River Basins Comprehensive Study

Comprehensive Study Appendix D Hydraulic Technical Documentation of the Comprehensive Study

CVFPP .... Central Valley Flood Protection Plan

Delta.......................... Sacramento-San Joaquin Delta

DWR.......................... California Department of Water Resources

msl............................ mean sea level

SPFC......................... State Plan of Flood Control

State .... State of California

USACE...................... U.S. Army Corps of Engineers

USGS .... U.S. Geological Survey

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